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ON REMOTE SENSING OF WATER CLOUDS FROM SPACE

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ABSTRACT

A new method for the determination of the effective radius and the liquid water path of water clouds from spectral measurements of the reflection is developed. It is based on approximate analytical solutions of the radiative transfer equation and geometrical optics approximations for local optical characteristics of cloudy media, recently obtained by authors.

INTRODUCTION

The investigation of microphysical properties of water clouds from space is an important source of information about cloudy media on a global scale. There has been an increasing number of studies pertaining to retrieval theories and methods for obtaining cloud optical thickness and particle size from multispectral radiometers on satellites (Curran and Wu, 1982; Platnick and Twomey, 1994; Han et al., 1994; Nakajima and Nakajima, 1996). All of them are based on numerical solutions of the radiative transfer equation for plane parallel media. The task of this contribution is to introduce a simple method of particle size determination from the reflection function measurements. This method is based on asymptotic radiative transfer equation solutions for thick, weakly absorbing light scattering layers, and geometrical optics approximations for the local optical characteristics of water clouds.

REFLECTION FUNCTION OF WATER CLOUDS

Water clouds can be considered as thick, weakly absorbing light scattering media in the visible and the near infrared regions of the spectrum. It follows for the reflection function $R(\mu_0,\mu,\psi)$ of such media (Zege et al., 1991; Kokhanovsky & Zege, 1996):

$$R(\mu_0,\mu,\psi) = R_\infty(\mu_0,\mu,\psi)\exp(-Fy) - \Pi g(\mu_0)g(\mu)\exp(-y[1+z]) +$$

$$+ A\Pi g(\mu_0)g(\mu)/(1-Ar), \qquad (1)$$

where

$$g(\mu) = \frac{3}{7}(1+2\mu), \quad \Pi = \frac{\sinh(y)}{\sinh(y[1+z])}, \quad F = \frac{g(\mu_0)g(\mu)}{R_\infty(\mu_0,\mu,\psi)}, \quad r = e^{-y} - \Pi e^{-y(1+z)}, \qquad (2)$$

$$y = 4\sqrt{\frac{\sigma_{abs}}{3\sigma_{ext}(1-\langle\cos\theta\rangle)}}, \quad z = 0.75(1-\langle\cos\theta\rangle)\tau, \quad \tau = \sigma_{ext}L. \qquad (3)$$

Here A is the albedo of the Lambertian underlying surface, $\langle\cos\theta\rangle$ is the asymmetry parameter, σ_{ext} and σ_{abs} are the extinction and absorption coefficients of cloudy media, L is the geometrical thickness of a cloud, τ is the optical thickness, μ_0 and μ are the cosines of the

solar zenith angle ϑ_0 and the observation angle ϑ respectively, ψ is the azimuth, r is the spherical albedo of the cloud, and $R_\infty(\mu_0, \mu, \psi)$ is the reflection function of a nonabsorbing infinite cloud with the same phase function as the absorbing cloud being considered. There is not the analytical solution for the function $R_\infty(\mu_0, \mu, \psi)$. Nevertheless it should be pointed out that the function

$$R_\infty(\mu_0, \mu) = \frac{1}{2\pi}\int_0^{2\pi} R_\infty(\mu_0, \mu, \psi)\,d\psi \tag{4}$$

does not depend very much on the local optical properties of scattering media and

$$R_\infty(\mu_0, \mu) = \frac{1+4\mu\mu_0}{2(\mu+\mu_0)} \tag{5}$$

for water clouds with high accuracy (Zege et al., 1991). This solution for the reflection function can be used at small observation angles (i.e., nadir measurements).

The values of σ_{ext}, σ_{abs}, $<\cos\theta>$ depend on the effective radius of particles $r_e = \dfrac{<r^3>}{<r^2>}$, where brackets mean an average over the particle size distribution. They can be calculated within the framework of the Mie theory or the geometrical optics approximation. In the last case one can use the following solutions (Kokhanovsky & Zege, 1995):

$$\sigma_{ext} = \frac{1.5C_v}{r_e}\left\{1+\frac{1.1}{(kr_e)^{2/3}}\right\}, \quad \sigma_{abs} = 1.2\alpha\, C_v(1+s)(1-\alpha r_e),$$
$$1-<\cos\theta> = 0.118 + \frac{0.5+0.2c}{(kr_e)^{2/3}} - 0.75c\left\{0.1+\frac{1}{2(kr_e)^{2/3}}\right\}, \tag{6}$$

where $\alpha = 4\pi\chi/\lambda$, $c = 2\alpha r_e$, $s = 0.34(1-\exp(-8\lambda/r_e))$, $k = 2\pi/\lambda$, C_v is the volumetric concentration of particles, λ is the wavelength, and χ is the imaginary part of the refractive index of drops. The relative error of Eqs. (6) is less than 10 percent for $\lambda < 2.2\mu m$, $4 \le r_e \le 20\mu m$.

From Eqs. (3) and (6) one can obtain the following simple formulae:

$$y = 4\sqrt{\alpha r_e}, \quad z = \frac{0.12w}{r_e\rho}\left(1+6(kr_e)^{-2/3}\right), \tag{7}$$

where $w = C_v\rho L$ is the liquid water path and ρ is the density of water. The accuracy of the analytical solution (1) for the reflection function of water clouds using (2), (5), (7) was investigated by Kokhanovsky & Zege (1996). It was found, that the relative error of calculation of the reflection function is less than 15 percent at solar zenith angles less than 50^0, for nadir observations and $\tau > 13$, $\lambda < 2.2\mu m$, $4 \le r_e \le 12\mu m$. One example of such comparison is presented in Figure 1.

Thus, simple solutions (1), (2), (5), (7) can be used to investigate the dependence of the reflection function of water clouds from their microstructure parameters at small observation angles.

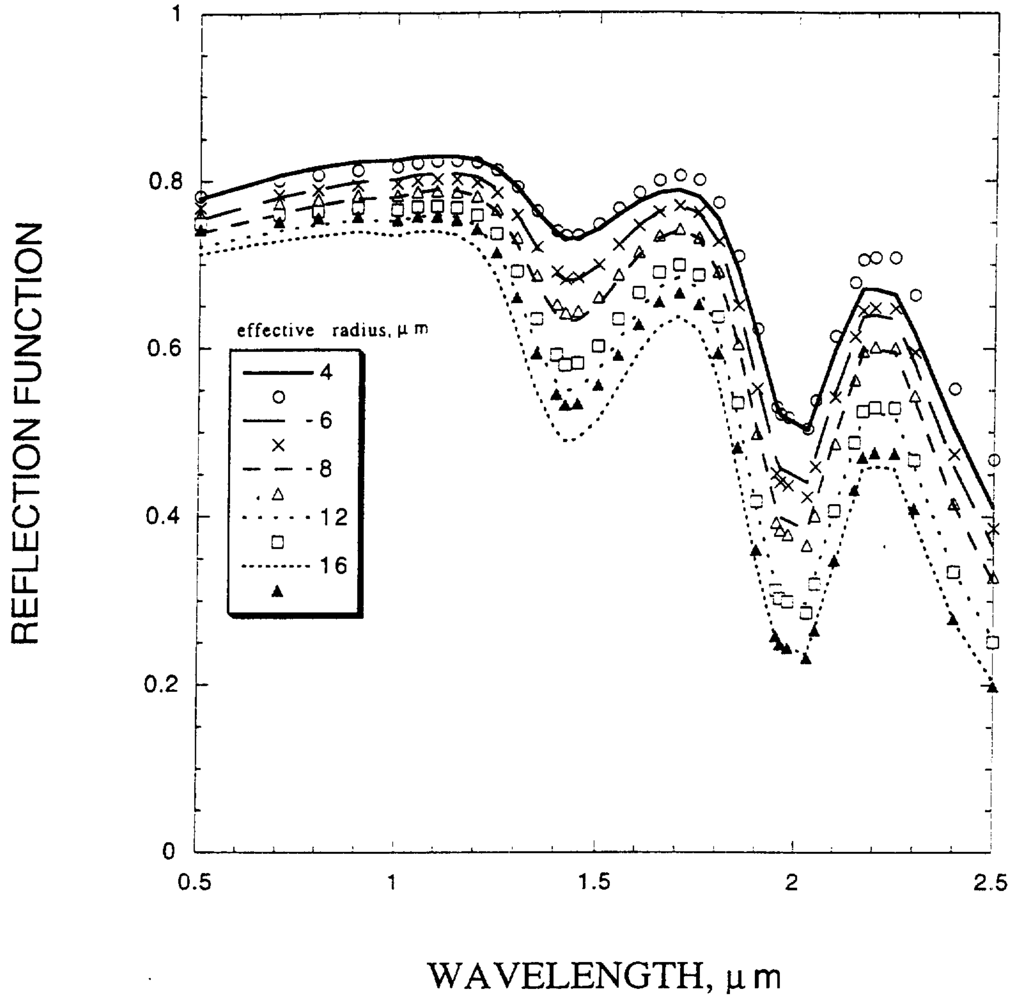

Fig. 1. The reflection function of water clouds for different values of the effective radius of droplets at $\tau = 30$, $\vartheta_0 = 45^0$, $\vartheta = 0^0$ and $A = 0$. The results were obtained by exact (solid lines) and approximate (see Eq.(1)) methods.

RETRIEVAL ALGORITHM

Eqs. (1), (2), (5), (7) can be used to retrieve the effective radius and the liquid water path of water clouds. To do so one should measure the reflection function at two wavelengths (in the visible and the near-infrared regions of the spectrum). In the visible band water clouds do not absorb solar radiation and $y = 0$ (see Eq.(7)). In this case it follows from Eq.(1):

$$z(\lambda_1) = \frac{g(\mu_0)g(\mu)}{R_\infty - R(\lambda_1)} - \frac{1}{1-A}. \tag{8}$$

Here $R(\lambda_1)$ is the measured reflection function at $\lambda = \lambda_1$ and $z(\lambda_1)$ is the value of z at $\lambda = \lambda_1$. In the near infrared region of spectrum, clouds are weakly absorbing and one should solve the following equation to find the value of the effective radius of drops (see Eq.(1)):

$$R(\lambda_2) - R_\infty(\mu_0,\mu)\exp(-Fy(\lambda_2)) + \Pi(\lambda_2)g(\mu_0)g(\mu)\exp(-y(\lambda_2)[1+z(\lambda_2)]) - \\ - A\Pi(\lambda_2)g(\mu_0)g(\mu)/(1-Ar(\lambda_2)) = 0. \tag{9}$$

Here the value of $R(\lambda_2)$ is the measured reflection function at $\lambda = \lambda_2$. Note, that the value of

$$z(\lambda_2) = \frac{1+6(2\pi r_e/\lambda_2)^{-2/3}}{1+6(2\pi r_e/\lambda_1)^{-2/3}} z(\lambda_1) \tag{10}$$

in Eq.(9) depends on the effective radius of particles and the value of $z(\lambda_1)$, which can be found from Eq.(8). The value $y(\lambda_2)$ depends on the value of the effective radius of particles only (see Eq.(7)). Thus, it is possible to find the value of r_e from Eq.(9). The liquid water path can subsequently be determined from Eq.(7).

To estimate the error of this technique the calculations of reflection functions $R(\lambda_1)$ and $R(\lambda_2)$ of water clouds with different microphysics were performed. The doubling method of the solution of the radiative transfer equation was used for this purpose. The extinction and absorption coefficients as well as the phase function of cloud media at $\lambda_1 = 0.659\mu m$, $\lambda_2 = 2.13\mu m$ were calculated with the use of the Mie theory. After that the effective radius of drops was retrieved form Eqs.(8)-(10). It was found that the error of the effective radius determination is less than 15 percent for sun angles, ranged from 30 to 45 degrees at nadir observations. The maximum error (30 percent) is located at glory and rainbow scattering angles, where the geometrical optics approximation is characterized by small accuracy.

CONCLUSION

A new simple technique to retrieve the effective radius of water drops from satellite measurements of reflection functions of water clouds is proposed. It is based on the asymptotic solutions of the radiative transfer theory for thick weak absorbing layers and the geometrical optics approximation for local optical properties of water clouds.

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